

MINIATURIZED ANTENNAS FOR COMPACT SOLDIER COMBAT SYSTEMS

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ABSTRACT

We simulate miniature loop and patch antennas with reactive elements embedded in the substrate of the antenna. To lower the antenna's effective resonant frequency and reduce the physical size of the antenna, we considered split-ring resonators (SRRs) as the antenna's inductive substrate material. Simulation results indicate a size reduction of up to thirty-eight percent is possible using this technique.

1. INTRODUCTION

To meet the demands of modern on-the-move mobile communications, miniaturization of antennas is essential. Compact antenna design allows a soldier to carry an antenna embedded in his or her uniform or even on a helmet, which minimizes electromagnetic interference with other electronic devices.

Since there exists a common communication channel around 2.4 GHz, we considered antennas that are electrically responsive in that frequency range. Typical resonant antennas, such as monopole and patch antennas, are either a quarter- or a half-wavelength, respectively, in one dimension. At 2.4 GHz, this corresponds to 6.25 cm (~2.5") and 3.125 cm (~1.25"). A popular antenna in the communication community is an omnidirectional rectangular resonant loop antenna whose dimensions are a quarter-wavelength on each side. The dependence of antenna's dimensions on wavelength poses a strict limitation on the ability to reduce the physical size of an antenna while maintaining its resonant frequency.

However, it is possible to reduce the physical size of an antenna by introducing reactive elements between the antenna and the ground plane. Since the resonant frequency of an antenna is inversely proportional to its total inductance (L) and capacitance (C), which includes the inductance and capacitance of the antenna and any paths to ground. If one increases either the inductance or capacitance in the path to ground, to maintain the resonant frequency, the antenna's inductance

or capacitance must be reduced, which can be achieved by reducing the dimension of the antenna.

However, increasing capacitance narrows the useable bandwidth around the antenna center frequency. In contrast, increasing inductance increases bandwidth, which is more desirable. Unfortunately, inductive elements are typically based on ferromagnetic materials, which have a weak electromagnetic response at GHz frequencies. To overcome this, we propose using artificial magnetic materials, in particular, split-ring resonators (SRRs), which have been shown to exhibit paramagnetic behavior well into the GHz frequency range (Yen et. al, 2004).

The resonant nature of SRRs and their application to antenna miniaturization has been studied before (Mirza et al, 2005, Karkkainen et.al, 2005, Ikonen et. al, 2005). In this paper, we extend the concept presented in (Karkkainen et. al., 2005) to loop antennas and investigate the effect of different substrate materials, i.e., fill factor of the SRRs and their orientation, on the resonant frequency of the antenna. We also present similar analysis for a miniaturized patch antenna. Moreover, we studied both the loop and patch antenna's radiation pattern and gain, and their variation with the introduction of SRRs. The paper concludes with a brief discussion of the simulation results obtained thus far using both Ansoft HFSS software and our in-house Finite Difference Time Domain (FDTD) code.

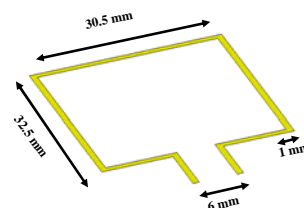


Fig. 1(a). Loop antenna

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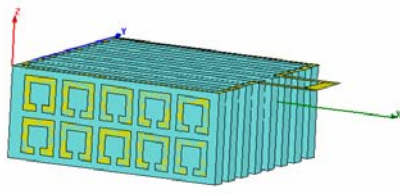


Fig. 1(b). Loop antenna on a stack of split ring resonators

2. LOOP ANTENNA MINIATURIZATION

We designed a loop antenna, represented in Fig. 1(a), approximately one quarter-wavelength on each side, such that its total perimeter was approximately one wavelength. For an antenna with a resonant frequency of 2.55 GHz in free space ($\lambda = 118$ mm), the loop antenna was 30.5 mm x 32.5 mm. Further, to increase inductance, we introduced two rows of five SRRs imprinted on an FR4 substrate, as represented in Fig. 1(b). Each SRR was 5 mm x 5 mm. To cover the entire area underneath the loop, we used eight 2 mm x 13 mm substrate slabs. The spacing between adjacent slabs was 2 mm. We simulated the operation of both configurations using Ansoft HFSS using lumped ports as the source. As shown in Fig. 2(a), when we introduced the FR4 slabs without any SRRs, the antenna's resonant frequency shifted to 2.24 GHz. With SRRs imprinted on the FR4 substrate the resonant frequency of the antenna was 1.97 GHz. Since the percentage shift in resonant frequency was 23%, we reduced the loop antenna dimensions by 23% to 23.6 mm x 25 mm and repeated the analysis. As shown in Fig. 2 (b), the resonant frequency shifted back to 2.55 GHz. This demonstrates that the small loop antenna resonates at the same frequency as its physically larger counterpart.

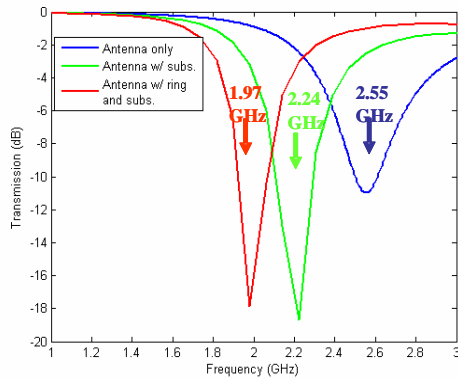


Fig. 2(a). Resonant frequency of the loop antenna

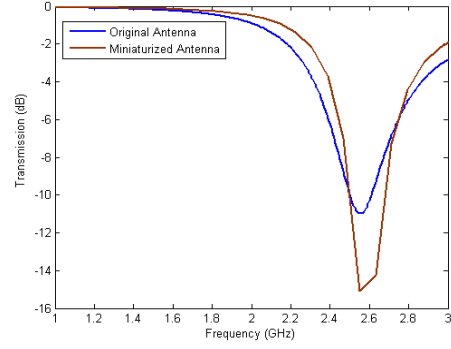


Fig. 2(b). Resonant frequency of the miniaturized loop antenna

2.1 Effect of Substrate Material, Package Density and Orientation of SRRs on the Miniaturization of Loop Antennas

We also considered three different substrate materials for the slabs without changing the orientation, size, or shape of the SRRs. Since resonant frequency is inversely proportional to the refractive index of the material, we noted a reduction in resonant frequency with an increase in substrate dielectric permittivity. Thus, as shown in Fig. 3(a), using FR4 ($\epsilon = 4.4$) the resonant frequency shifted from 2.55 to 1.97 GHz; with glass ($\epsilon = 5.5$) the resonant frequency was 1.8 GHz and with Rogers RO3010 ($\epsilon = 10.2$) the frequency was further reduced to 1.76 GHz.

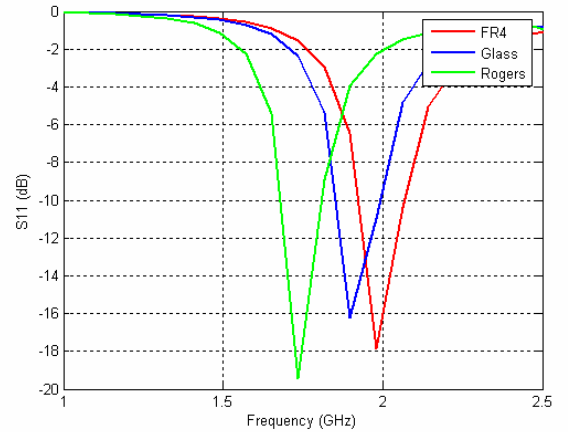


Fig. 3(a). Resonant frequency of the loop antenna with different substrates

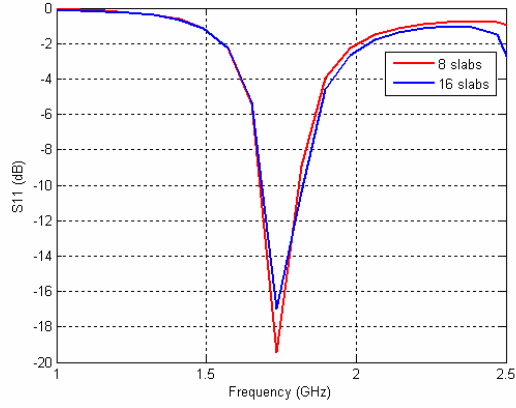


Fig. 3(b). Effect of the package density of the SRR on the resonant frequency of the loop antenna

We further studied the packaging density of the SRRs by increasing the number of slabs using RO3010 as the substrate material. As shown in Fig. 3(b), no change in the resonant frequency of the antenna was observed when the number of slabs was increased from eight to sixteen and stacked together. A physical explanation for such an observation is given in the following section.

Finally, we implemented a new ‘box’ configuration with the substrate slabs as shown in Fig. 4(a). RO3010 slabs with the SRRs were placed strategically underneath only the metal portion of the loop instead of covering the entire open area underneath the antenna. This was done to ensure that all the SRRs underneath the loop see the magnetic field generated by the antenna, which is perpendicular to their orientation. As shown in Fig. 4(b), we noted that the resonant frequency of the antenna was 1.7 GHz for the case of two substrate slabs per side. Following this, we increased the number of slabs per side to four and observed a reduction in the resonant frequency to 1.58 GHz, as shown in Fig. 4(b). This resulted in a reduction of the loop size by 38%! Due to computer memory limitations we could not simulate a configuration with a larger number of slabs per side.

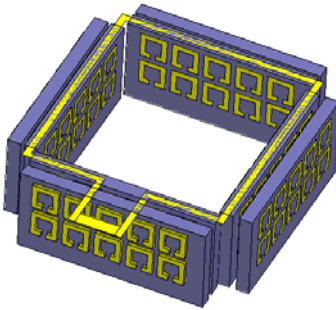


Fig. 4(a). New ‘box’ substrate configuration

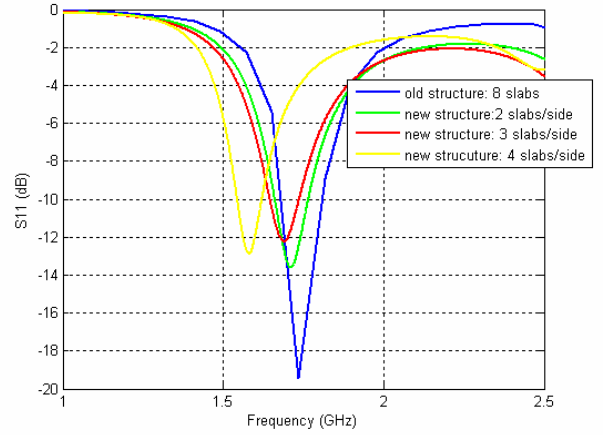


Fig. 4(b). Resonant frequency of the loop antenna with the ‘box’ substrate

The results from the box configuration indicate that the magnetic field in the middle of the loop must be zero, which is possible if the current on the two sides of the loop are in opposite directions. Thus, our preliminary understanding is that substrates containing SRRs in the middle region of the loop do not contribute to lowering the resonant frequency further. In contrast, as indicated in Fig. 4(b), the fields on the edges do contribute. Note that as additional slabs are added to the edges the resonant frequency is reduced. Thus, to miniaturize a loop antenna, the ‘box’ configuration of Fig. 4(a) is preferred over the stack configuration of Fig. 1(b). In the following section we perform a similar analysis for the patch antenna, which was studied previously in (Karkkainen et. al., 2005).

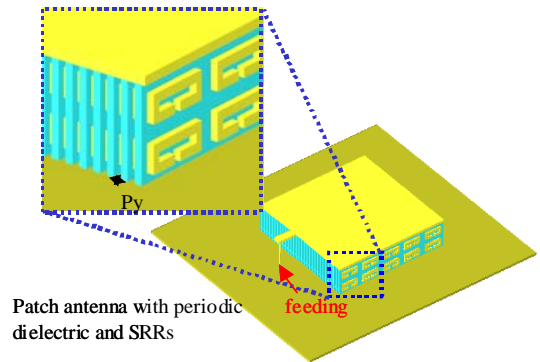


Fig. 5(a). Stack of split-rings underneath a patch antenna.

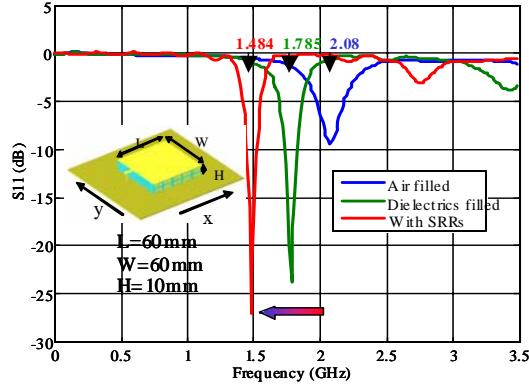


Fig. 5(b). Patch antenna resonant frequency

3. PATCH ANTENNA MINIATURIZATION

Fig. 5(a) represents a stack of ring resonators sandwiched between a patch antenna and a ground plane. The spacing between stacks of rings is 2 mm periodicity. We assumed a coaxial line was used to feed the patch antenna structure, which was analyzed using our custom FDTD code.

As in the case of the loop antenna, the magnetic fields from the antenna induced currents on the rings, which results in a corresponding shift in the resonant frequency, as shown in Fig. 5(b). In this figure, the blue curve was the resonant frequency of the antenna at 2.08 GHz for a dimension of 60 mm x 60 mm and the red curve at 1.484 GHz was the resonant frequency after introducing the rings in the structure. With the FR4 substrate only the resonant frequency of the antenna shifted to 1.785 GHz from its original value of 2.08 GHz. Details of the substrate parameters can be found in (Karkkainen et. al., 2005), where similar observations were made.

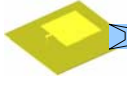
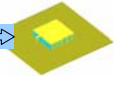
Antenna	Air filled	SRRs+Dielectric filled
		
Dimension (W x L x H) mm	60 x 60 x 10	42.8 x 42.8 x 7.1
Reduction factor	1	0.71

Fig. 6(a) Miniaturization of the patch antenna

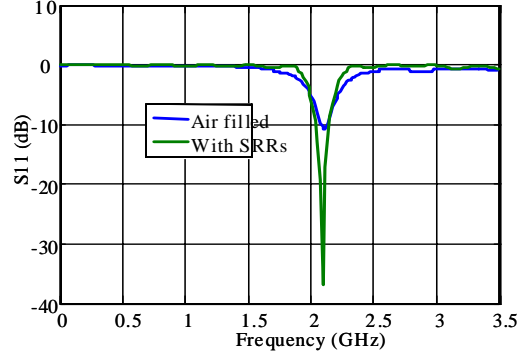


Fig. 6(b). Resonant frequency of miniaturized patch antenna

Since the percentage of frequency shift was 28.6%, we reduced the patch antenna by a similar amount, as shown in Fig. 6(b). In this case, the resonant frequency shifted back to the original frequency of the antenna at 2.08 GHz. As a result, the new shifted frequency had a higher Q-value, which was expected as a result of introducing the SRRs underneath the antenna. As pointed out in the previous section, a similar observation was made in the case of the loop antenna.

3.1 Effect of Package Density of SRR on the Miniaturization of Patch Antenna

In addition to the above analysis, we also studied the packaging density of the ring structures. We expected that increasing the density of the rings would shift down the resonant frequency even further and, thereby, enable further reduction in antenna size. This is demonstrated in Fig. 7 where the spacing between stacks was varied from 2 to 5 mm. The resonant frequency of the structure with 2 mm spacing was lower than that for the 5 mm structure. This result is in contrast to what we observed for a loop antenna. The primary reason for this is that the current distribution on a patch antenna is different than that for a loop antenna, which induces a different interaction with the SRR structure.

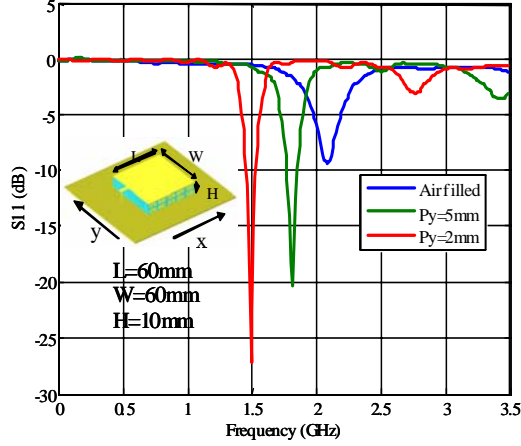


Fig. 7. Impact of package density of SRRs on antenna resonance.

4. RADIATION PATTERN OF THE LOOP AND PATCH ANTENNA

We investigated the radiation patterns and the gain of the loop antenna with and without the SRR slabs. For the loop antenna shown in Fig. 1(b) the rings are stacked in the y-direction. For this configuration, as shown in Figs. 8(a) and (b), the radiation pattern was symmetric in both the XZ plane and YZ plane. The gain value of the antenna was 3.79 dB. This value changed only to 3.41 dB when the rings were introduced, as shown in Figs. 8(a) and (b). The reason for such a small change in gain is due to the small surface area of the loop, hence interaction with the antenna and the rings is minimal. We note that the radiation pattern of the loop was omni directional as was expected.

We also investigated the radiation pattern and gain of the patch antenna with and without the SRR slabs as shown in Fig. 5(a). In this case the off-centered feed to the antenna was in the x-direction and the slabs stacked in the y-direction. The gain of the patch was 9.619 dB and the radiation pattern was directional as expected. Because the feed for the antenna was off-centered the resulting radiation pattern was not symmetric, as shown in Figs. 9(a) and (b). With the introduction of the SRRs the gain decreased to 5.94 dB. We believe this is due to the large surface area of the patch and the corresponding increased interaction with the SRRs. Also, the side lobes in the radiation pattern are due to the non-infinite ground plane used in the simulation.

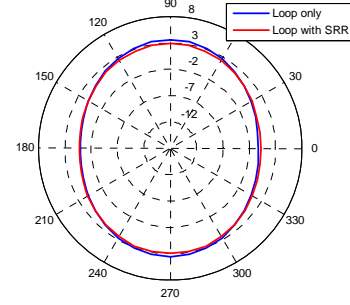


Fig. 8(a). Radiation pattern of loop antenna on the XZ plane

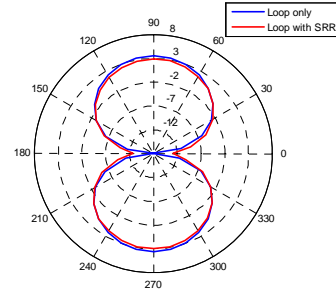


Fig. 8(b). Radiation pattern of loop antenna on the YZ plane

CONCLUSION

In summary, we studied the miniaturization of loop and patch antennas using SRRs, which are artificial inductive materials, embedded in the substrate. We investigated the effect on miniaturization of the antenna with the variation of different substrate parameters. We also proposed a new box-like pattern for the SRR configuration for the loop antenna, which led to a 38% miniaturization in antenna size. We noted that by increasing the SRR stacks underneath the patch antenna, the size reduction factor can be decreased. Also, the radiation patterns of the miniaturized antennas were briefly discussed. We found that the radiation pattern of the loop antenna was omni directional and that the gain value changed only slightly with the introduction of the SRR slabs underneath the antenna. However, in the case of the patch antenna we observed that it was very directive and the gain of the antenna decreased by only a few dB when miniaturized with the SRR slabs. In the future we will investigate the effect of the size and shape of the SRRs on the miniaturization of the antennas. We also plan to fabricate the simulated structures and verify simulation results with experimental data.

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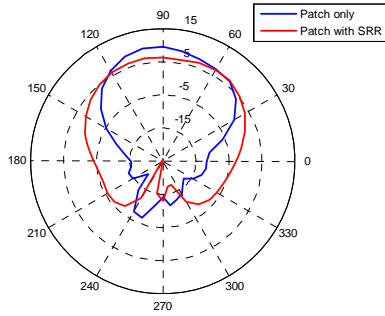


Fig. 9(a). Radiation pattern of patch antenna on XZ plane

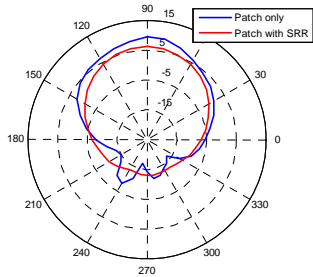


Fig. 9(b). Radiation pattern of patch antenna on YZ plane